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MAINTENANCE OPTIMIZATION OF INDUSTRIAL CHIMNEYS EXPOSED TO CARBONATION

Abstract

The paper is focused on the deterioration of industrial reinforced concrete chimneys caused by carbonation. It is considered that a chimney has to be repaired when more than 30% of its surface is affected by visible corrosion-induced cracks. An optimal maintenance strategy aims at the postponement of this state beyond the intended service life of the chimney with minimum maintenance costs.

Keywords

Carbonation, concrete cover, industrial chimney, service life, optimization

1 INTRODUCTION

Reinforced concrete structures are commonly exposed to unfavorable environmental influences. Jointly with chloride ingress, the carbonation of concrete cover leads to major economic losses [1,2]. During carbonation, chemical reactions of air-contained carbonates and portlandite in concrete gradually decrease the pH of concrete, which leads to the depassivation of reinforcement and its subsequent corrosion. The carbonation progress depends particularly on the quality of concrete and on external factors like humidity and the air concentration of CO_2.

The process of carbonation is described in fib Model Code 2010 [3] or in the IAEA [4].This paper is particularly focused on structures in power industry where the use of protective coatings of chimneys, having a significant effect on carbonation progress, is optimised using probabilistic method.

The process of carbonation can hardly be entirely avoided. If reinforcement corrosion is initiated, repair of a structure requires considerable financial resources. The suitable protective technology still evolves – contemporary coatings are able to retain their protective properties for up to 15 years [5]. New construction works in energetics are commonly designed for 40 years design service life [6].

2 COMPARISON OF EXPERIMENTAL DATA AND THEORETICAL MODELS FOR CONCRETE CARBONATION

The analysis is based on the data obtained from monitoring of four chimneys of fossil power plants in the Czech Republic, particularly focused on the outer surface of the chimneys. Fig. 1 shows the values of the carbonation depth measured at the outer surface of industrial chimneys during the

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period of 50 years. Monitoring was focused on reference spots located over the entire height of the chimneys. The average values from each measurement are displayed in Fig. 1. For comparison, the IAEA model [4] for chimneys unprotected by coating is also shown (time-invariant coefficient of variation $V_D \approx 0.4$ is estimated on the basis of long-term measurements provided by an operator, see also [7]). The IAEA model is defined by the following general relationship:

$$D(t) = 9.47\, R\, t^{0.5}\, (4.6x - 1.76) \tag{1}$$

where:

$D(t)$	–	is carbonation depth in time [mm],
t	–	is age of the chimney [year],
$x \approx 0.5$	–	is water to cement ratio [-] and
$R = \alpha\beta$	–	is a constant in mm / √year

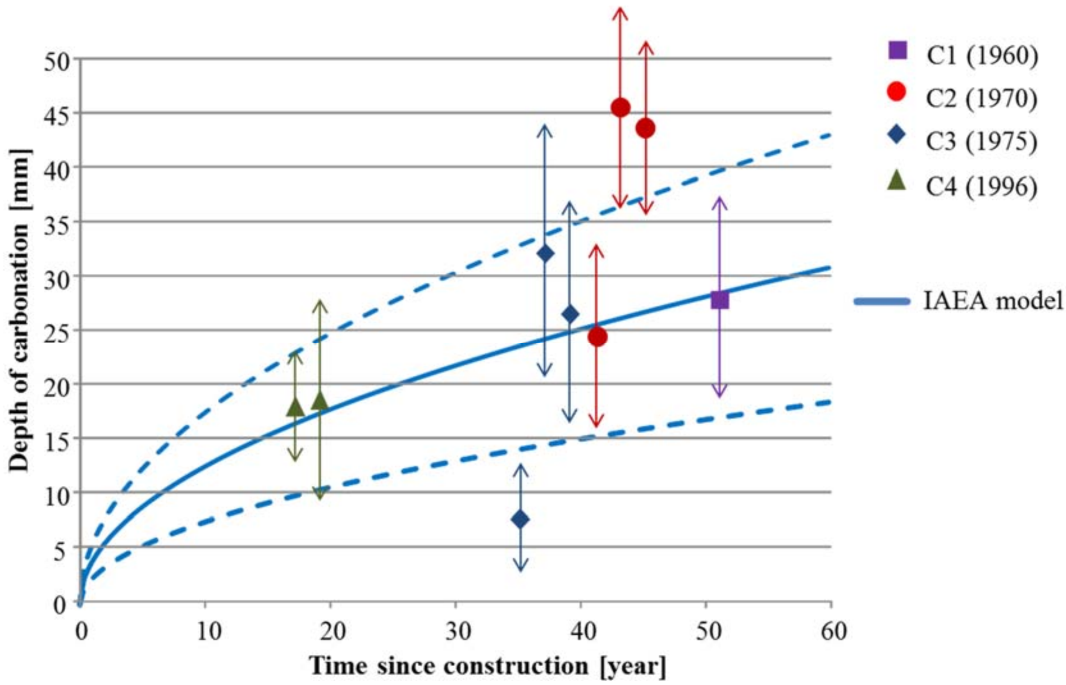

Fig. 1: Comparison of the measured carbonation depths observed on four chimneys (C1-C4) with the IAEA model [2] for the chimneys unprotected by coating

R varies depending on the surface coating on the concrete (β) and whether the concrete has been exposed to outdoor or indoor environment (α). The coefficient α is 1.0 for outdoor concrete and β is 1.0 for structures without a protective layer and 0.8 for coated structures.

All measurements are shown in Fig. 1, each point indicates an average of 5 measurements, and the arrows indicate the interval +/- standard deviation. The data in Fig. 1 show that the measured values tend to exceed the values predicted by the IAEA model [4]. Updated model based on measured data predicts faster progress compared to the model based on the recommendations of the IAEA. Simplified equation for the carbonation progress can be written as:

$$D(t) = a\sqrt{t} = 4.5\sqrt{t} \tag{2}$$

The constant a is obtained by fitting the curve to measurements. Moreover, protective coatings are commonly applied on concrete structures. The constant a in Equation (2) takes into account outdoor or indoor conditions, the effects of water to cement ratio and of protective coating. The constant is reduced based on recommendation of IAEA model [4] by 20% if the surface is protected by coating. More advanced models for $D(t)$ were proposed in [8-10].

Normal distribution is considered for concrete cover and depth of carbonation; in the following studies several probabilistic models will be critically compared to identify a most appropriate model. Coefficients of variation $V_C = \sigma_C / \mu_C \approx 0.2$ and $V_D(t) = \sigma_D(t) / \mu_D(t) \approx 0.4$ were obtained from measurements.

3 MAINTENANCE OPTIMIZATION

It is considered that chimneys are always protected by a suitable coating after construction. Maintenance of reinforced concrete chimneys depends on the durability of a coating, which decelerates the carbonation process. According to [11], it can be considered that a coating loses its protective properties after about 15 years. Before application of the new coating, the original coating is removed by sand-blasting.

The following scenarios of maintenance, selected for this study, are based on the discussions with fossil power plants operators:

- Scenario 0 – no coating during the lifetime of a chimney
- Scenario 1 – new coatings after 10 years since commissioning
- Scenario 2 – new coatings after 10 and 20 years
- Scenario 3 - coating applied every 10 years.

The effect of the scenarios on carbonation progress is shown in Fig. 2.

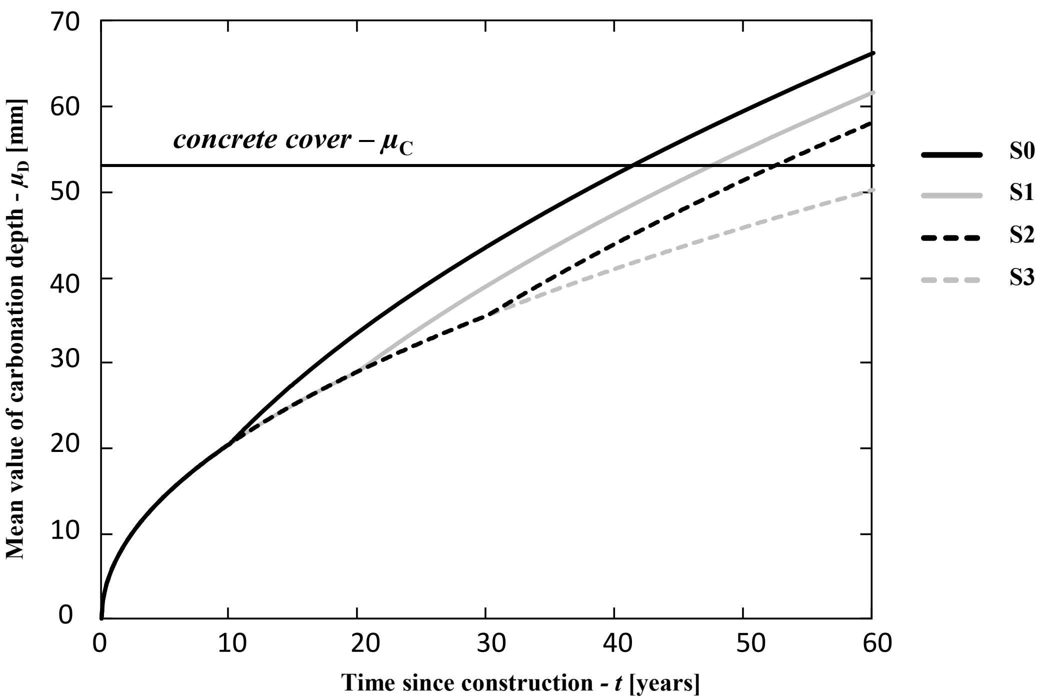

Fig. 2: Carbonation ingress with time since construction for the scenarios S0-S4.

In accordance with the methodology provided in [5], a chimney should be repaired (concrete cover is replaced in severally deteriorated areas, structural surface is cleaned by sand-blasting and protective coating is applied on the whole surface) when the area affected by visible corrosion-induced cracks reaches 30% of the surface. This criterion is consistent with the requirements in [12, 13].

The average period between the time when carbonation reaches the reinforcement, and the time when cracks due to corrosion appears on the surface, is approximately five years [14].

Reliability index for carbonation of a concrete cover can be obtained from the following relationship:

$$\beta(t) = [\mu_C - \mu_D(t)] / \sqrt{[\sigma_C^2 + \sigma_D^2]} \quad (3)$$

where:

μ_C – is the mean value of the concrete cover [mm],

σ_C – is the standard deviation of the concrete cover [mm],

$\mu_D(t)$ – is the mean depth of carbonation [mm] and

σ_D – the standard deviation of the carbonation depth [mm].

The area a_{corr} affected by corrosion-induced cracks is estimated as follows:

$$a_{corr}(t) = \mathrm{Prob}[C < D(t\text{-}\Delta t_{\mathrm{cr1}})] = \Phi[-\beta(t\text{-}\Delta t_{\mathrm{cr1}})] \quad (4)$$

where $\Phi[-]$ is the standard normal distribution and Δt_{cr1} is the time between corrosion initiation and cover cracking. $\Delta t_{\mathrm{cr1}} \approx 5$ years is based on the recommendations outlined in JCSS [14].

Left part of Fig. 3 shows the reliability index β according to Equation (3) and the right part displays the relative surface area of the chimney affected by corrosion in time t. A threshold indicating the need of repair, $a_{corr} = 0.3$, corresponds to reliability index $\beta \approx 0.5$.

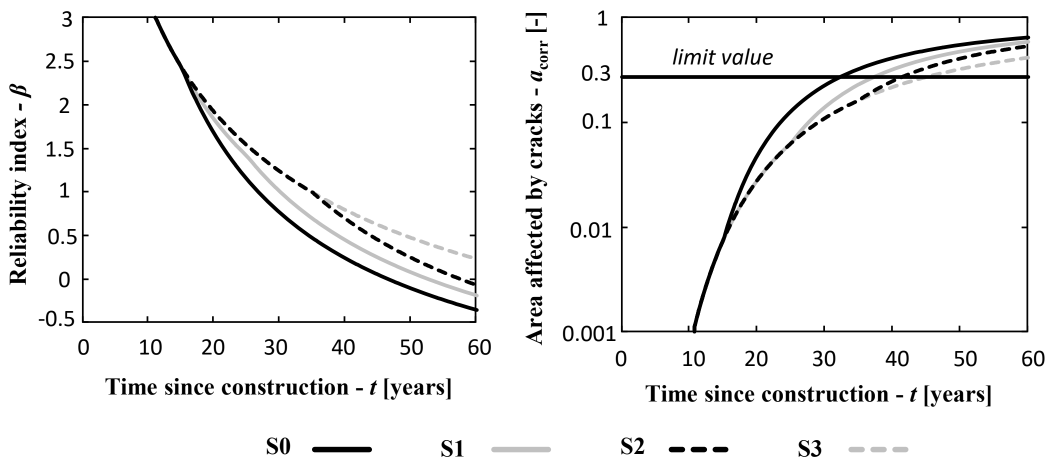

Fig. 3: Reliability index β (left) and relative surface area of the chimney affected by corrosion a_{corr} (right) as functions of time t.

4 EXAMPLE OF MAINTENANCE OPTIMIZATION

The repair optimization is performed similarly as in the study [15]. Optimization does not include the first coating, its costs are part of the construction cost. Two types of costs are considered:

- C_{coat} – the cost per m^2 of coating recovery (removal of an original coating, application of a new coating),
- C_{corr} – the cost per m^2 of the removal of concrete in areas affected by cracks induced by corrosion, cleaning of reinforcement, concrete repair.

Based on discussions with experts from power industry, no costs are associated with unplanned outage as repairs of chimneys are planned for periods of regular (scheduled) outages of power units. Based on cost analysis, the estimated ratio is $C_{\mathrm{corr}} / C_{\mathrm{coat}} = 10$. Relationship for optimisation over Scenarios S0-S3 is:

$$C_{tot}(t)/(A\ C_{coat}) = [n + a_{corr}\ (C_{corr}/(A\ C_{coat}))] \qquad (5)$$

where:

A – is the area of the surface of chimney [m^2],

n – the number of coating recoveries,

a_{corr} – the relative area affected by visible corrosion-induced cracks, where counted if it reaches 0,3; 0 otherwise [-],

$C_{tot}(t)/(A\ C_{coat})$ – the total relative costs of repairs related to one coating recovery of the entire area of the chimney [-],

Fig. 4 shows variability of relative repair costs of the surface of a reinforced concrete chimney in time (related to the cost of one coating recovery of chimney). It is observed that if service life of a chimney is 40 years, it is appropriate to choose Scenario S2; for the service life of 50 years the scenario S0 should be selected and for service life of 60 years the Scenario S1 represents the optimum maintenance strategy.

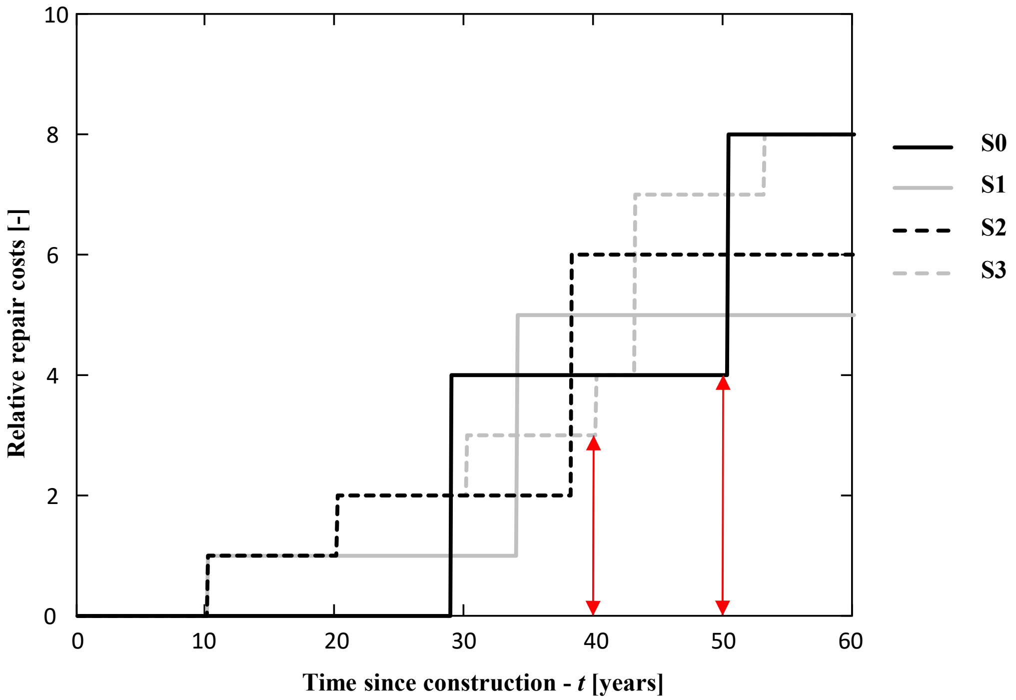

Fig. 4: Relative repair costs for Scenario S0-S3 in time *t*

5 CONCLUSIONS

The study is focused on optimising maintenance costs of a industrial reinforced concrete chimney considering a time series of measured carbonation depths. It is shown in Fig. 4 that the optimal maintenance scenario depends on a required service life of a structure. For example, the scenario when protective coating is applied every 10 years till the time of commissioning represents an optimal strategy for a service life of 40 years, which is commonly considered in design of industrial chimneys and cooling towers. For the structural service life of 50 years, minimum maintenance costs are reached when a structure is repaired when 30% of the chimney surface is affected by cracks induced by corrosion.

Further research activities include:

- Validation of models for carbonation progress on the basis of a larger number of experimental data for different ages of industrial chimneys and cooling towers
- Investigation of the effect of discount rate in economic optimization. That should be used in Equation (5) to convert future investments to present value.

ACKNOWLEDGMENT

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LITERATURE

[1] TEPLÝ B., CHROMÁ M. & ROVNANÍK P. Durability assessment of concrete structures: reinforcement depassivation due to carbonation. *Structure and Infrastructure Engineering* Vol. 6 , Iss. 3,2010

[2] KÖLIÖ A., PAKKALA A. T., ANNILA P. J., LAHDENSIVU J. & PENTTI M. Possibilities to validate design models for corrosion in carbonated concrete using condition assessment data. *Engineering Structures* 75:539–549, September 2014

[3] *fib*. *fib Model Code for Concrete Structures 2010*. Lausanne: fib, 2013.

[4] IAEA. *Guidebook on non-destructive testing of concrete structures*, International Atomic Energy Agency, Vienna, 2002.

[5] MARKOVÁ J. & SÝKORA M. *Methodology for assessment of service life of industrial chimneys and cooling towers in ČEZ, a.s.*, in Czech, report of Klokner Institute, CTU in Prague, No. 314120J000, 2014

[6] *ISO 16204:2012 Durability — Service life design of concrete structures*.

[7] HOLICKÝ M., HOLICKÁ N. Probabilistic optimisation of concrete cover exposed to carbonation. Proc. of the Internatioal RILEM-JCI Seminár, Ein-Bokek, Israel 2006, ISBN 2-912143-89-6, pp. 384-393.

[8] PAPADAKIS, V. G.: (2000) Effect of supplementary cementing materials on concrete resistance against carbonation and chloride ingress, *Cement and Concrete Research* 30 (2) (2000) pp. 291-299.

[9] PAPADAKIS, V. G & TSIMAS, S.: (2002) Supplementa1y cementing materials in concrete. Part I: Efficiency and design. *Cement and Concrete Research* 32 (I 0) (2002) pp. 1525-1532.

[10] KERŠNER, Z. & NOVÁK, D., TEPLÝ, B. & BOHDANECKY, V. Karbonatace betonu, koroze výztuže a životnost chladící věže, *Sanace* 4 I 1996. s. 21-23.

[11] MOZARYN, T. & KOKOWSKA, J. The service life of coating systems applied on cooling towers – laboratory study and in-situ investigations, *RILEM Workshop on Long-Term Performance of Cementitious Barriers and Reinforced Concrete in Nuclear Power Plants and Waste Management*, ISBN: 978-2-35158-072-1, 2009.

[12] HERGENRÖDER, M. *Zur statistischen Instandhaltungsplannung für bestehende Bauwerke bei Karbonatisierung des Betons und möglicher Korrosion der Bewehrung*. Berichte aus dem Konstruktiven Ingenieurbau, TU Munich 4/92, 1992.

[13] ENGELUND, S. & SØRENSEN J.D. A probabilistic model for chloride-ingress and initiation of corrosion in reinforced concrete structures. *Structural Safety* 20 (1998): pp. 69-89.

[14] JCSS. *JCSS Probabilistic Model Code*, chapter Environmental Attack (periodically updated, online publication). Joint Committee on Structural Safety, 2001. <www.jcss.byg.dtu.dk>.

[15] DONADIO M., FIÚZA C. & TAYLOR D. Life Cycle Assessment of Repair and Maintenance Solutions for Cooling Towers, *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2013*, Wroclaw University of Technology, Poland.